# Sandia National Laboratories Validation Workshop: Structural Dynamics Application

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## 1 Introduction

The purpose of this article is to describe a structural dynamics-based virtual application that is for use as a validation exercise. This application, which closely mimics real scenarios of interest to structural dynamics professionals, contains the following elements:

- A **target application**, which provides both a decision context and an accompanying regulatory requirement, and serves as the basis for the study.
- A **subsystem** that isolates phenomena deemed important by problem specialists, albeit in a configuration that is not fully-relevant to the target application.
- An **accreditation system** that is more complex, and more relevant to the target application; it is a configuration that is more expensive to prototype and to test.
- A realistic set of virtual experimental data. These data include:
  - Multiple sets of experimental results for sub-elements of our application process, which are less-relevant to our application than more complex accreditation system.

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Our sub-element is manifested in our subsystem. The lower costs associated with performing experiments on the subsystem level (building multiple, nominally-identical prototypes, instrumenting and testing these prototypes, etc) make it more feasible to acquire multiple data sets.

  - The data also include results of virtual experiments on the accreditation system. These results come from a smaller number of experiments due to the cost factor.
  - We provide the following data from our virtual experiment series, which is available via anonymous ftp (see Appendix B for information on how to retrieve this data): (1) Excitation and displacement, velocity, and acceleration time-histories for each test; (2) Estimated acceleration frequency response function (FRF) data for each test; and, finally, (3) A set of modal parameters that is reduced from this response data for each test. These data are available to each participant as Matlab mat-files. Note that the archive also contains m-files; the contents of these m-files are discussed below.

- By design each of our configurations possesses uncertainties in the form of ignorance and variability. For simplicity, we have elected to isolate these uncertainties in the subsystem:
  - The subsystem contains elements that are assumed to come from a population with inherent variabilities. Our limited number of sampled structures yields limited information regarding the trends present in these variabilities. The presence of inherent variablities and ignorance in their regard are a well-known phenomena observed in our laboratories.
  - There are also discrepancies between the physics model we provide for the subsystem, which is a linear elastic, viscous-damped model represented completely by the supplied modal properties, and the characteristics of the virtual processes themselves. These discrepancies can only be manifested in our comparisons between experimental observations and simulations of these experiments using our model. This ignorance is another phenomenon observed regularly in our experiences.

- We emphasize that all of our virtual experiments involve virtual structural specimens that are models, too. These models define the underlying "truth"; and, while in practice there are myriad obstacles in the path of the experimentalist and the analyst for establishing this truth, we limit the breadth of these obstacles by (1) assuming that the structural elements in the various configurations other than the subsystem are known, and (2) assuming that we have been able to make perfect, noise free measurements with perfect devices that do not alter the underlying process in any way.

- Regardless of the configuration under consideration, we seek to appeal to participants who have no expertise in structural dynamics. To address questions on the modeling process, we provide an overview of it in Appendix A, and, additionally, we provide the means for participants to acquire system output through a series of Matlab-based function m-files that require the user to provide, for the subsystem and accreditation system, an excitation time-history, such as, for example, one of the provided excitation time-histories from the test array, along with a set of modal parameters describing the subsystem; this set, in a probabilistic context could be thought of as a realization. For the target application system the excitation is provided for the user. The only required input for this case is a set of modal parameters for the subsystem. The m-files associated with all of these configurations are in the same archive file that contains the experimental data discussed above.

- One final note. An additional, and important, issue in the validation process is understanding the effect that data quantity has on the ability to assess the quality of the predictive model that results from it. In this regard, we have provided results for 20 nominally identical subsystems, which were each subjected to virtual experiments provided as a means to calibrate our model, and, similarly, 20 subsystems provided to validate it. We have also provided results from three nominally identical accreditation configurations. We have done this to provide a means for participants to address the data quantity aspect in any way they see appropriate.

Our target application is a beam of varying cross-sectional properties on an elastic foundation exposed to a distributed shock loading supporting a flexible substructure that is attached via a weakly nonlinear connection. The regulatory requirement is associated with the response at a particular location on the substructure to this shock; namely, that the maximum acceleration at this point must be kept below a critical threshold to ensure its functional integrity. The various approaches to establishing our ability to make simulation-based predictions of the target application with sufficient confidence are what is of interest in this exercise.

The building blocks to be used by the invited analysts are detailed in the remainder of this document. We provide a brief outline here:

First, we consider a suite of random vibration experiments on the subsystem, including the connection, that we attach to ground and that we propose for calibrating the parametric model. We emphasize that this is not a model-building exercise; we will provide all data, inputs and outputs, acquired via our experiments in a way that is similar to that available in a real modal survey. We also provide the results of our modal analyses that we perform using the acquired time-history data.

Next, we provide the results of a second suite of experiments that expose a different set of these (nominally identical) subsystems to shocks of various amplitudes. It is expected that this information will be useful in a validation context.

Finally, we provide information on our more fully-relevant system: Our subsystem is connected, again, using the same attachment system as in the calibration and validation experiments, to a beam of constant cross-section. The beam is exposed to local, single-point shocks.

We end this discussion by noting that, in this structural dynamics application, as in most that we're aware of in practical applications, we require that a linear structural dynamics model for the subsystem be used even though the actual system possesses a weak nonlinearity. The various configuration models are completely characterized by the physical models for the beam systems, which are assumed to be completely known, and the modal models for the subsystem, which possesses all the problem uncertainties. To avoid problems that might originate with such factors as the selection of integration schemes, and any parameters native to them, and to facilitate the process for those analysts not well-versed in the various elements of modal testing and analysis, we provide Matlab m-files that produce time-histories for each of the system configurations, the subsystem, accreditation system, and, if desired the application system, given the analyst-provided array of modal data, namely, the modal frequencies, damping, and mode shapes, required for the subsystem, and external excitation time-histories.

# 2 Target Application

Consider the system shown in Figure 1. The structure consists of a beam with varying cross-sectional properties on an elastic foundation with a substructure connected to it at a point via a weakly nonlinear connection. The condition of concern is whether or not sensitive components of the substructure will survive the shock, and we propose that it will as long as the acceleration at a particular point, namely mass 3 at the top of the substructure, is below a certain threshold. Specifically, we require that the acceleration of mass 3 in the subsystem to satisfy

$$\mathrm{Prob}\{\max_{t>0} |a(t)| > 1.8(10^4)\mathrm{in/sec}^2\} < 10^{-2}$$

where Prob$\{\ \cdot\ \}$ denotes the probability of the occurrance of the event described in the braces. We are interested primarily in the approaches and processes the participants develop for establishing confidence in their assessments under the conditions presented.

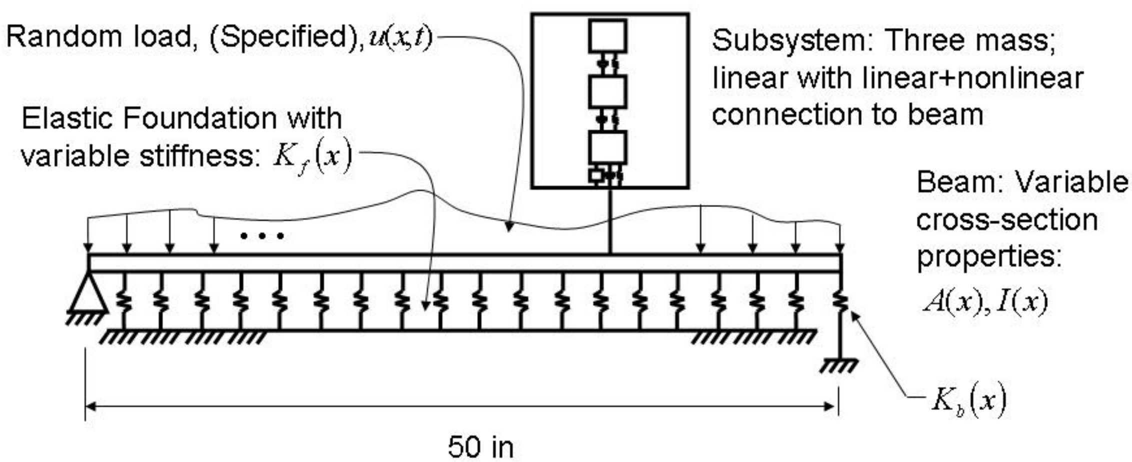


Figure 1: Target Application

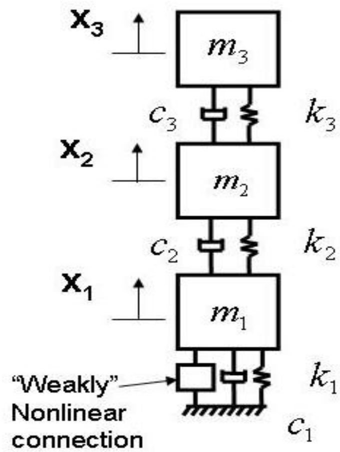


Figure 2: Subsystem for Calibration: Component with Connections

# 3 Subsystem Calibration

The subsystem, shown in Figure 2, consisting of the 3-mass component mounted on the beam in the target application, along with its nonlinear connection to the beam, is considered for calibration.

The calibration process will use the results of a random vibration study on 20 nominally identical systems, each selected from a virtual pool. Each of these selected systems will be subjected to a suite of tests consisting of stationary, band-limited random vibration (Gaussian pseudo white noise) entailing three excitation levels. A typical input/output record are given in Figure 3. Among the group of systems there are inherent variabilities, and this fact is manifested in the given system responses.

For the virtual tests, each structural specimen is assumed to have motion restricted to the vertical direction, is connected to ground as depicted in Figure 2, and, finally, the excitation is applied to the mass $m_1$, and the measured responses are the accelerations at $m_1$, $m_2$, and $m_3$. For the sake of those participants with little or no experience with structural dynamics applicatons, we note that these responses correspond to the three degrees of freedom (DOF) of the configuration.

We also take this opportunity to re-emphasize one final time that this exercise is one for which physics-based model building is neither requested nor allowed; we will provide all structural models relevant to our virtual systems. We strongly suggest that this would be an excellent time for those who are unfamiliar with structural dynamics topics to consider reviewing the material

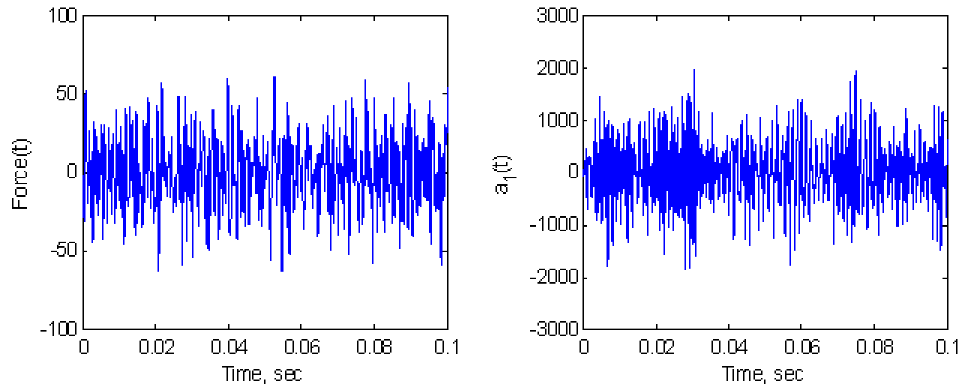


Figure 3: Typical Random Vibration Input/Output Time History Set

in Appendix A for an overview of the analysis approaches and the attendant terminology.

The response acceleration data are first reduced to complex-valued frequency response function (FRF) data—a magnitude plot for one such FRF is shown in Figure 4, then further reduced to modal parameters, modal frequencies, $\omega_i$, mode shape vectors, $\phi_i$, and modal damping, $\zeta_i$, relative to critical damping, for each of the 20 tested articles. The participants should be able to readily associate the datasets in the Matlab files properly; we give the modal parameters from the first of the tested structures for each excitation level in Tables 1, 2, and 3 to facilitate this association.

Recall that additional data from these, and entire datasets from all remaining experiments will be made available via anonymous ftp.

# 4 Subsystem Validation

For the validation process, where we once more consider the subsystem shown in Figure 2, we replace the random vibration test series with a shock/free-decay study. We consider another 20 nominally identical systems. Each of these systems will be subjected to a suite of three tests, and these individual tests will be performed using a pre-determined nominal excitation level. The objective of each of these test suites will be to exercise the subsystem at different response levels, which are related to the magnitude and duration of their corresponding shock input. The test inputs will consist of a series three nominally identical haversine shocks, which

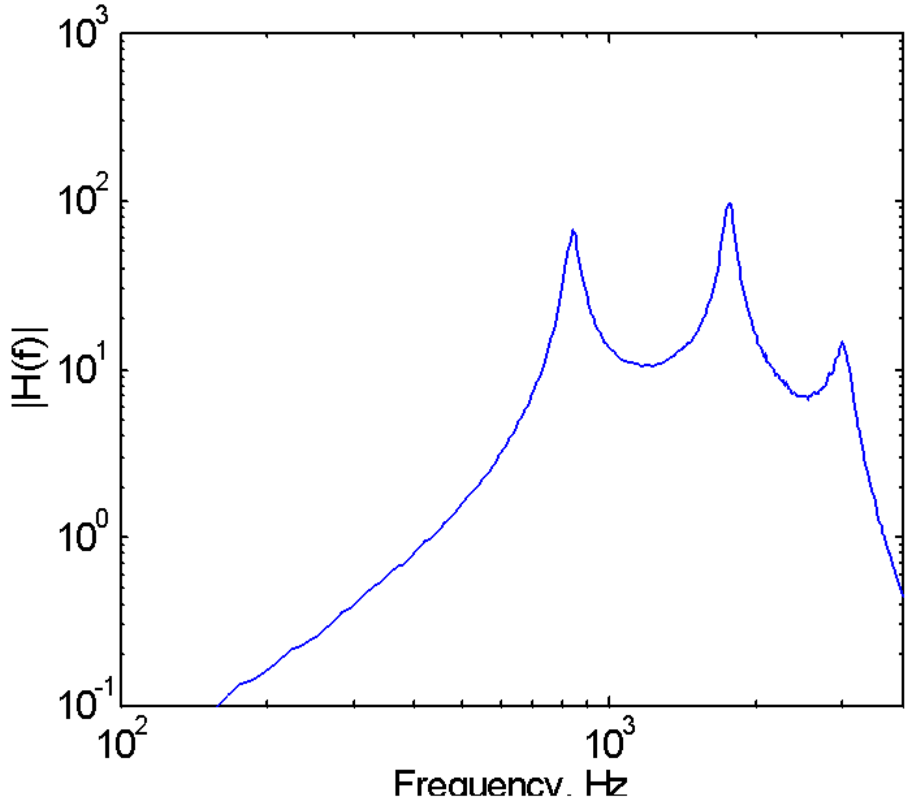


Figure 4: Typical Acceleration FRF from Calibration Tests

| **Modal Parameters**<br>Random Vibration, Low-Level Excitation | | | |
|---|---|---|---|
| Sample # | $[\omega_i]$ (rad/sec) | $[\zeta_i]$ (Critical) | $[\Phi_i]$ (Mass-Normalized) |
| 1 | $\begin{bmatrix} 5287.4 \\ 11084 \\ 19534 \end{bmatrix}$ | $\begin{bmatrix} 0.023875 \\ 0.02107 \\ 0.029197 \end{bmatrix}$ | $\left[ \begin{pmatrix} 0.43851 \\ 3.9324 \\ 7.9404 \end{pmatrix} \begin{pmatrix} 0.87806 \\ 5.9996 \\ -4.5794 \end{pmatrix} \begin{pmatrix} 5.2073 \\ -1.1637 \\ 0.1652 \end{pmatrix} \right]$ |

Table 1: Results of Calibration Experiments: Low-Level Excitation

| **Modal Parameters**<br>Random Vibration, Mid-Level Excitation | | | |
|---|---|---|---|
| Sample # | $[\omega_i]$ (rad/sec) | $[\zeta_i]$ (Critical) | $[\Phi_i]$ (Mass-Normalized) |
| 1 | $\begin{bmatrix} 5282.2 \\ 11067 \\ 19228 \end{bmatrix}$ | $\begin{bmatrix} 0.024353 \\ 0.0215 \\ 0.034723 \end{bmatrix}$ | $\left[ \begin{pmatrix} 0.44947 \\ 3.8268 \\ 7.6923 \end{pmatrix} \begin{pmatrix} 0.94529 \\ 6.0049 \\ -4.6244 \end{pmatrix} \begin{pmatrix} 5.2288 \\ -1.2322 \\ 0.1831 \end{pmatrix} \right]$ |

Table 2: Results of Calibration Experiments: Mid-Level Excitation

| **Modal Parameters**<br>Random Vibration, High-Level Excitation | | | |
|---|---|---|---|
| Sample # | $[\omega_i]$ (rad/sec) | $[\zeta_i]$ (Critical) | $[\Phi_i]$ (Mass-Normalized) |
| 1 | $\begin{bmatrix} 5271.6 \\ 11056 \\ 19002 \end{bmatrix}$ | $\begin{bmatrix} 0.027857 \\ 0.023875 \\ 0.035418 \end{bmatrix}$ | $\left[ \begin{pmatrix} 0.47485 \\ 3.8492 \\ 7.7059 \end{pmatrix} \begin{pmatrix} 0.99473 \\ 5.9927 \\ -4.6449 \end{pmatrix} \begin{pmatrix} 5.0465 \\ -1.2322 \\ 0.18884 \end{pmatrix} \right]$ |

Table 3: Results of Calibration Experiments: High-level Excitation

are assumed to vary in amplitude due to realistic constraints on regulating shock inputs in the lab, and averaged. A typical time-history set of the input/output pair is given in Figure 5.

As was the case for the calibration tests, the problem is assumed to have motion restricted to the vertical direction, and the measured responses are the accelerations at $m_1$, $m_2$, and $m_3$; however for this case the excitation is applied at $m_2$.

Also, as previously, the acceleration time-histories are first reduced to frequency response function (FRF) data, then further reduced to modal parameters for each of the 20 tested articles. The modal parameters from the first test structure for each input level are given in Tables 4, 5, and 6.

As was the case in Section 3, all additional data will be made available to the analysts via anonymous ftp.

# 5 Accreditation Configuration

The so-called accreditation test configuration, shown in Figure 6, will provide a more fully-relevant scenario for establishing the suitability of the model for the purpose of developing confidence in the subsequent prediction for the application scenario described in Section 2.

As can be seen in the figure, the subsystem is mounted on a uniform beam that is simply supported on one end and supported with a linear spring at the other, and subjected to a single-input shock loading scheme similar to that employed in the validation tests. The measured

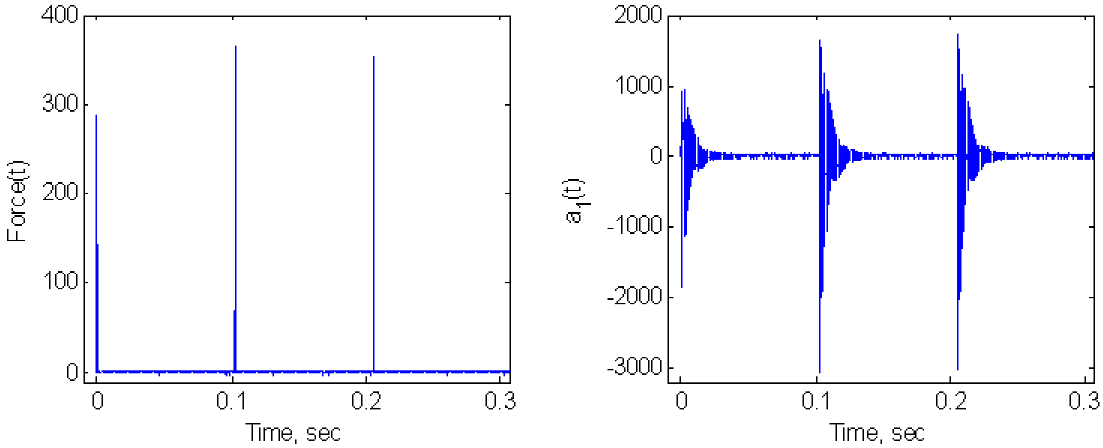


Figure 5: Typical Shock Input/Output Time History

| **Modal Parameters**<br>Shock, Low-Level Excitation | | | |
|---|---|---|---|
| Sample # | $[\omega_i]$ (rad/sec) | $[\zeta_i]$ (Critical) | $[\Phi_i]$ (Mass-Normalized) |
| 1 | $\begin{bmatrix} 4658.6 \\ 9807.7 \\ 17391 \end{bmatrix}$ | $\begin{bmatrix} 0.020649 \\ 0.019898 \\ 0.028414 \end{bmatrix}$ | $\begin{bmatrix} \begin{pmatrix} 0.40715 \\ 3.7494 \\ 7.5889 \end{pmatrix} \begin{pmatrix} 0.85347 \\ 5.9721 \\ -4.5389 \end{pmatrix} \begin{pmatrix} -5.4041 \\ 1.2265 \\ -0.17553 \end{pmatrix} \end{bmatrix}$ |

Table 4: Results of Validation Experiments: Low-Level Excitation

| Modal Parameters<br>Shock, Mid-Level Excitation | | | |
|---|---|---|---|
| Sample # | $[\omega_i]$ (rad/sec) | $[\zeta_i]$ (Critical) | $[\Phi_i]$ (Mass-Normalized) |
| 1 | $\begin{bmatrix} 4654. \\ 9788. \\ 17024. \end{bmatrix}$ | $\begin{bmatrix} 0.020649 \\ 0.020236 \\ 0.02731 \end{bmatrix}$ | $\left[ \begin{pmatrix} 0.4252 \\ 3.706 \\ 7.4683 \end{pmatrix} \begin{pmatrix} 0.90069 \\ 5.9061 \\ -4.5205 \end{pmatrix} \begin{pmatrix} -4.931 \\ 1.2035 \\ -0.18251 \end{pmatrix} \right]$ |

Table 5: Results of Validation Experiments: Mid-Level Excitation

| Modal Parameters<br>Shock, High-Level Excitation | | | |
|---|---|---|---|
| Sample # | $[\omega_i]$ (rad/sec) | $[\zeta_i]$ (Critical) | $[\Phi_i]$ (Mass-Normalized) |
| 1 | $\begin{bmatrix} 4649.3 \\ 9785.4 \\ 16901. \end{bmatrix}$ | $\begin{bmatrix} 0.020649 \\ 0.020236 \\ 0.030985 \end{bmatrix}$ | $\left[ \begin{pmatrix} 0.43135 \\ 3.6995 \\ 7.4448 \end{pmatrix} \begin{pmatrix} 0.91858 \\ 5.8594 \\ -4.4992 \end{pmatrix} \begin{pmatrix} -5.0449 \\ 1.2621 \\ -0.19573 \end{pmatrix} \right]$ |

Table 6: Results of Validation Experiments: High-Level Excitation

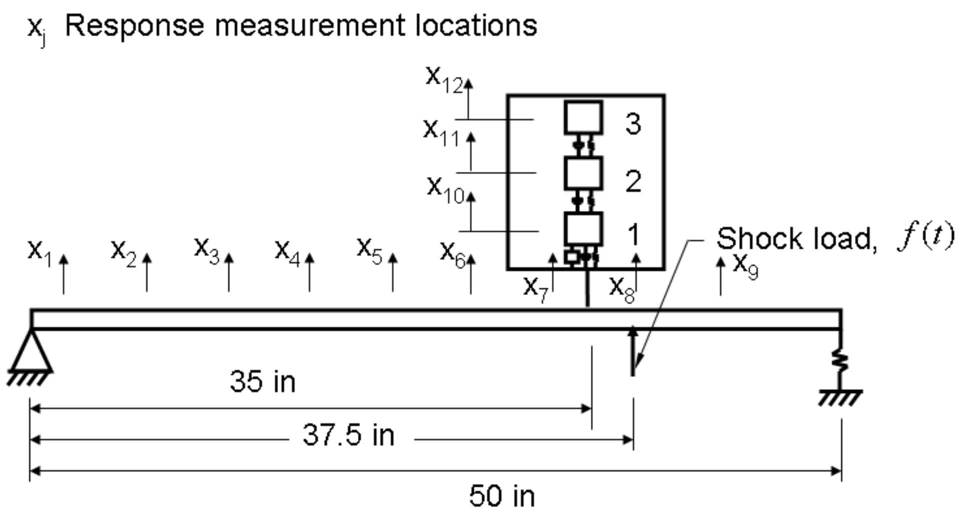


Figure 6: Accreditation Configuration

| **Modal Frequencies and Damping:** $\omega, \zeta$<br>Single-Point Shock Input | | |
|---|---|---|
| Sample # | $[\omega_i]$ (rad/sec) | $[\zeta_i]$ (Critical) |
| 1 | $\begin{bmatrix} 980.77 \\ 3432.7 \\ 5656.3 \\ 9274.5 \\ 10165. \end{bmatrix}$ | $\begin{bmatrix} 0.019898 \\ 0.020236 \\ 0.019898 \\ 0.019898 \\ 0.019125 \end{bmatrix}$ |

Table 7: Results of Accreditation Experiments: Frequencies and Damping

responses are the linear accelerations at twelve points on the combined structure. The input and outputs are depicted in Figure 6; specific geometric locations will be provided in the companion dataset.

Note especially that the degree of freedom for subsystem mass number three is response degree of freedom twelve in the combined structural system.

Also, due to the high cost of building test specimens for accreditation systems, the number of specimens tested is typically limited; we limit this number to three.

A similar pattern of analysis is followed for this system and its modal test setup as was carried out for the subsystem tests: The measured acceleration time-history data were first reduced to FRFs, then modal parameters were estimated for each tested structure.

The modal frequencies and damping values from the first of these tests are given in Table 7, and Table 8 contains the mass-normalized mode shape vectors, as columns in the listed matrix, for this same tested structure.

| Mode Shape Vectors<br>$\boldsymbol{\Phi}$ (Mass-Normalized, Column-Oriented)<br>Single-Point Shock Input, Sample 1 |
|---|
| $$\begin{bmatrix} 0.89304 & -1.7976 & -1.0893 & 2.6981 & 1.0429 \\ 1.7097 & -3.1231 & -1.6926 & 3.4638 & 1.2733 \\ 2.3792 & -3.6367 & -1.5365 & 1.7441 & 0.51527 \\ 2.8411 & -3.2278 & -0.67707 & -1.243 & -0.62876 \\ 3.0495 & -2.0529 & 0.53099 & -3.3884 & -1.239 \\ 2.9762 & -0.50661 & 1.6027 & -3.2219 & -0.77371 \\ 2.6116 & 0.86388 & 2.16 & -1.0164 & 0.56375 \\ 1.9655 & 1.4877 & 2.1292 & 1.3235 & 2.0933 \\ 1.0983 & 1.2463 & 1.5424 & 2.2902 & 2.7978 \\ 2.3382 & 1.4898 & 2.0445 & 0.7533 & 0.9638 \\ 2.4099 & 2.5778 & -1.336 & 2.6923 & -5.3052 \\ 2.4682 & 3.6317 & -6.5051 & -2.2674 & 3.2204 \end{bmatrix}$$ |

Table 8: Results of Accreditation Experiment 1: Modal Vectors

# Appendices

## A Structural Dynamics Modeling Concepts

In this section, we provide a brief overview of various aspects of linear structural dynamics models. There are a number of references where one can delve more deeply into this subject matter; we give two: [1] and [2] as starting points.

The underlying models in this exercise are all assumed to be linear, time-invariant, viscous-damped, multi-degree-of-freedom (mdof) structural dynamics models. Such models take the form:

$$\boldsymbol{M}\ddot{\boldsymbol{x}} + \boldsymbol{C}\dot{\boldsymbol{x}} + \boldsymbol{K}\boldsymbol{x} = \boldsymbol{f} \tag{A.1}$$

where $\boldsymbol{M}$, $\boldsymbol{C}$, and $\boldsymbol{K}$ are the mass, damping, and stiffness matrices, respectively, $\boldsymbol{f}$ is the external excitation, and $\boldsymbol{x}$ is the vector containing the physical displacements; time differentiation is denoted by $\dot{(\ )}$ and $\ddot{(\ )}$, which correspond to first and second time derivatives, respectively, and are understood to operate on all elements of the corresponding vector.

## A.1 Modal Form

Equation (A.1) can be transformed into *modal coordinates* by:

1. Setting

$$\boldsymbol{x} = \boldsymbol{\Phi}\boldsymbol{q} \tag{A.2}$$

   where $\boldsymbol{q}$ are the modal coordinates, and $\boldsymbol{\Phi}$ is the modal matrix with columns consisting of mass-normalized mode shape vectors. We'll describe one method for obtaining these shortly.

2. Substituting (A.2) into (A.1); and,

3. Premultiplying the resulting equation by the transpose of $\boldsymbol{\Phi}$, $\boldsymbol{\Phi}^t$.

All of this yields the following system

$$\boldsymbol{\Phi}^t\boldsymbol{M}\boldsymbol{\Phi}\ddot{\boldsymbol{q}} + \boldsymbol{\Phi}^t\boldsymbol{C}\boldsymbol{\Phi}\dot{\boldsymbol{q}} + \boldsymbol{\Phi}^t\boldsymbol{K}\boldsymbol{\Phi}\boldsymbol{q} = \boldsymbol{\Phi}^t\boldsymbol{f} \; . \tag{A.3}$$

Properties of $\boldsymbol{\Phi}$ are known to diagonalize Eq (A.3), which is commonly expressed as

$$\boldsymbol{I}\ddot{\boldsymbol{q}} + 2\boldsymbol{\zeta}\boldsymbol{\omega}\dot{\boldsymbol{q}} + \boldsymbol{\omega}^2\boldsymbol{q} = \tilde{\boldsymbol{f}} \tag{A.4}$$

where $\boldsymbol{I}$ is the identity matrix, $2\boldsymbol{\zeta}\boldsymbol{\omega}$ is the diagonal damping matrix composed of entries from the scaled modal damping and modal frequency vector entries, $2\zeta_i\omega_i$ on the diagonal, and $\boldsymbol{\omega}^2$ is the diagonal modal stiffness matrix with entries that are squares of the modal frequencies, $\omega_i$. The transformed excitation is represented by $\tilde{\boldsymbol{f}}$. The relationships that each of these entities holds to the physical system can be readily identified by comparing them with their counterparts in Eq (A.3).

In this exercise, the modal parameters present in Eq (A.4) are collected first into two vectors, $\boldsymbol{\omega}$ and $\boldsymbol{\zeta}$, and the aforementioned mass-normalized modal matrix, $\boldsymbol{\Phi}$. We assume that the order in each of these arrays is in ascending order of modal frequency, and that they are consistent as a group; specifically, the parameters associated with mode $i$ correspond to the i$^{th}$ entry in each vector, as well as with the i$^{th}$ column in $\boldsymbol{\Phi}$.

## A.2 More On The Modal Representation

For lightly damped structures, the problem of computing the system modal properties and shape vectors, given the physical system matrices, involves solving a generalized eigenproblem. The mode shape vectors are the eigenvectors of the undamped oscillator under null excitation, and the square of modal frequencies are the eigenvalues. The expression is given below:

$$(\boldsymbol{K} - \omega_i^2 \boldsymbol{M})\boldsymbol{\phi_i} = \boldsymbol{0}, \quad i = 1, \ldots, n \tag{A.5}$$

There are numerous noteworthy properties of the collection of mode shapes and vectors; we are omitting any in-depth discussion of these here except to note that the mode shape vectors for our systems, which possess well-separated modal frequencies, simultaneously diagonalizes the mass and stiffness matrices—a property that was exploited in moving to Eq (A.4) from Eq (A.1).

Also, as has been indirectly demonstrated in our exercise, the modal damping matrix is assumed to be diagonalizable in exactly the same way as the mass and stiffness.

## A.3 Experimental Modal Analysis

While Eq (A.5) seems relatively straightforward, experimentalists are presented with a vexing problem: They don't have access to the system matrices necessary to take the analytical eigensolution approach (not to mention the correct number of degrees-of-freedom of these matrices, $n$). Instead, they have the physical specimen, which they can support, instrument, and excite in controlled laboratory experiments to indirectly estimate the modal parameters, $\boldsymbol{\omega}$, $\boldsymbol{\zeta}$, and $\boldsymbol{\Phi}$.

This process is an sophisticated affair, and the reader is directed to the books by Ewins [3], or Maia and Silva [4] for more complete descriptions of it. For our purposes, it suffices to recognize the major steps involved:

1. Select and implement a support scheme for the subject test article;
2. Select and implement response measurement scheme;
3. Select and implement an excitation scheme;
4. Instrument the test article, for example with accelerometers, and the excitation means; these commonly include an impact hammer, or electromagnetic shakers;
5. Acquire data for excitation and response (forces and acceleration time-histories);
6. Transform time-history data to frequency domain, via a process such as fast Fourier transformation (FFT);
7. Generate frequency response function (FRF) representations from the frequency domain data, and average appropriately;

8. Extract modal model parameters from FRF representations.

None of the steps in this process are trivial or obvious to the non-experimentalist. We provide information on each of these steps in the text of the document; and, for the sake of completeness, we provide all relevant data for each of the systems we have submitted to the virtual testing exercise. Specifically, we provide the excitation and response time-histories for each of our tests, the resulting FRF data, and the extracted modal model parameter sets.

## A.4 Putting Things Together

Finally, we reiterate our goal: This exercise is a means to synergize activities in, and develop a deeper understanding of, model validation processes. Thus, it is our intention that the modal parameter dataset when combined with Eq (A.4) yields complete information on the models that comprise our problem; no in-depth knowledge of experimental structural dynamics is required.

With the above point in mind, note that we will provide, in addition to the data cited above, Matlab modules for computing response time-history data, as well as $\max_t\{\|a(t)\|\}$, given user-specified inputs for both an excitation time-history and a set of modal parameters for the three-dof subsystem for each structural configuration, namely the Subsystem, Accreditation and Application configurations, of interest in this exercise.

# B Retrieving The Application Data and Function Files

As we discussed in Section 1, the various data and modeling considerations require that we make the information associated with this application available in some way other than directly listing it in this document.

The the data and Matlab m-file functions are available in archive format both as a `gzip`'d `tar` file, `vv_sd-challenge.tar.gz`, or as a Windows-compliant `zip` file, `vv_sd-challenge.zip`. A top-level general information file in pdf format, `sd_chall_README.pdf`, is included both individually and in the filesets making up each of the archives. This document is there to provide the participants with a detailed accounting of what is contained in the archive. We also include a MS Word document, `sd_chall_README.doc`, which is identical in content.

Finally, we have chosen to make our application information available to our participants via the Internet using `anonymous ftp` from our open network host, `endo.sandia.gov`.

A description of the process for obtaining one such file follows, but first we note that:

1. Most versions of `ftp` will default to your current userid, so you will need to ensure that you can override this default. In our example below, we do this with the `-n` argument to our call.

2. Security constraints require permissions that do not allow users to view the contents of the various directories. This means that it is imperative that you get to the correct place, and specify the filename that you intend to download without the use of wildcards. Any attempt to perform an `ftp`-based command that implicitly requires a read on the directories involved, such as `pwd`, `dir`, etc, will lead to strange results.

3. Our example download was performed on a Unix-based computer, and the interactive shell command prompts are indicated with a `>` at the beginning of a line.

In what follows, we give an example of a download of the file `vv_sd-challenge.tar.gz`, you must enter the correct name of the file you are retrieving:

```
> ftp -n endo.sandia.gov
Connected to endo.sandia.gov.
220 sass3075 FTP server (This computer is a Federal computer system
and is property of the United States Government.  It is for authorized
use only.  Users have no explicit or implicit expectation of privacy.)
ready.
500 'AUTH GSSAPI': command not understood.
Remote system type is UNIX.
Using binary mode to transfer files.
ftp> user anonymous
331 Guest login ok, send ident as password.
Password: <put-your-userid-here>
230 Guest login ok, access restrictions apply.
ftp> cd /pub/outgoing/jrredho
250 CWD command successful.
ftp> bin
200 Type set to I.
ftp> get vv_sd-challenge.tar.gz
local: stochasticfem.tar remote: vv_sd-challenge.tar.gz
200 PORT command successful.
150 Binary data connection for vv_sd-challenge.tar.gz (134.253.159.120,35285)
```

```
226 Binary Transfer complete.
3257 bytes received in 0.0014 seconds (2.3e+03 Kbytes/s)
ftp> quit
221 Goodbye.
```

# References


[1] R. Clough and J. Penzien. *Dynamics of Structures*. McGraw-Hill, Inc., New York, NY, 2 edition, 1993.

[2] W. T. Thomson. *Theory of Vibration with Applications*. Prentice Hall, Englewood Cliffs, NJ, 1981.

[3] D. J. Ewins. *Modal Testing: Theory and Practice*. John Wiley and Sons, 1984.

[4] N. M. M. Maia and J. M. M. E. Silva, editors. *Theoretical and Experimental Modal Analysis*. Mechanical Engineering Research Studies. Engineering Control Series, 9. Research Studies Press, 1st edition, 1997.